Using Surface Pressure to Improve Tropical Cyclone Surface Wind Retrievals form Synthetic Aperture Radar Imagery

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LONG-TERM GOALS

The calibration and validation of surface wind and stress retrievals from oceanic synthetic aperture radar (SAR) imagery is especially difficult in tropical cyclone (TC) conditions. The geophysical model functions (GMFs) that characterize the radar backscatter in terms of the near-surface wind vector for different viewing geometries are currently poorly characterized for the very high wind and strong ocean surface wave conditions that are present in all TCs. Our long-term goal is to develop a novel methodology to use surface pressure observations and a planetary boundary (PBL) model for calibration and validation (Cal/Val) of SAR GMFs in TC conditions and to produce scene-wide wind vector retrievals that are most consistent with the image backscatter, the GMF and the PBL model. We further working toward an improved understanding of atmospheric boundary layer processes and air-sea interaction in tropical cyclones.

OBJECTIVES

The objectives of this research are to (1) develop the methodology for deriving TC SLP fields from first-guess surface wind vector estimates based on various GMF formulations; (2) Use these SLP fields to derive surface wind vector retrievals that are, in a least-squares sense, a scene-wide optimal surface wind retrieval that is consistent with the observable linear features in the SAR image, the GMF and the PBL model; (3) Develop an optimization scheme that seeks the minimum adjustment to the surface wind vector field that will minimize the difference between observed (e.g. via drop sondes or buoys) and SAR-derived bulk pressure gradients across the image. The optimized surface wind field can then be used either to assess or adjust the GMF.

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APPROACH

Our research during the has performed as part of a SAR Tropical Cyclone Working Group in collaboration with Chris Wackerman of General Dynamics (GD), Jochen Horstmann of NATO Centre for Maritime Research and Experimentation (CMRE) and Hans Graber, Roland Romeiser and Michael Caruso of University of Miami. GD and CMRE have developed separate methods for estimating wind directions. In addition, CMRE has been developing “cross-pol” GMFs, which have a lot of promise in the high wind regime. The GD and CMRE wind directions are merged into a single wind direction product and incorporated into a new processing system (WiSAR) that produces surface wind vector maps at 1 km spacing. We use the WiSAR wind vector fields as input to our SLP pattern and SLP-filtered surface wind retrieval system.

During the first year of the project, an analytic two-layer model of tropical cyclone boundary layer dynamics (TCBL) was developed and tuned to historic Atlantic observations and to preliminary analysis of aircraft and other data from the Impact of Typhoons on the Pacific ocean (ITOP) field program of 2010. During the second year, we were able to review the preliminary analyses and examine the results more critically. This led to further improvements in the TCBL model to include corrections to the mean flow nonlinear dynamics due to storm motion-induced asymmetry.

The derived SLP patterns may be used as inputs to the PBL model to re-derive an “SLP-filtered” surface wind field. This product is a scene-wide estimate of the surface wind vectors that enforces consistency between the all of the wind vectors and the pressure fields. We have extensively documented this overall methodology and the high quality of our SLP fields and derived wind vectors using QuikSCAT and ASCAT scatterometer wind vector data in several papers (Patoux et al. 2003; 2008; 2011).

A key aspect of the conventional SAR wind vector retrievals is that often there are regions where no wind vectors are retrieved of where the retrieved wind vectors are determined to be less certain than. Part of the WiSAR processing development was determining a set of wind vector quality flags. In our sea-level pressure retrieval, we restrict the input to only include the highest-quality input vectors. Thus, there are often regions of the image that do not contribute to the sea-level pressure retrieval. However, when the SLP-filtered winds are calculated, we can fill-in the masked-out regions.

Our applications to TC conditions with SAR wind vectors have shown that both the directions and speed in the SLP-filtered winds can be significantly changed when compared to the Raw wind input. In particular, the GMFs in TC conditions work best when the surface winds are across the radar beam and work poorly when the radar beam looks either up- or down-wind. The SLP-filtered winds “fill-in” the low wind holes near the TC core in these up- and down-wind regions. They can also fill in regions in the SAR WiSAR product that have been masked due to rainy conditions or for being out of range of the GMFs. Prior to the ITOP field campaign, we had only a handful of good SAR cases to study with near-in-time in situ data (dropsondes and stepped-frequency microwave radiometer, SFMR, surface wind speeds). Examination of these cases has shown that the SLP-filtered wind speeds are a major improvement over the input wind speeds. A qualitative inspection of the wind directions suggests that they are more realistic than the input directions, which tend to have too little inflow in the inner core region. However, validation of wind directions is severely limited by a lack of reliable data.

It should be emphasized that since surface pressure fields are integral properties of the surface vector wind fields, wind adjustments must occur over a broad spatial region rather than just locally near the

pressure data. Thus, even though we use point wise pressure data, they imply wind corrections at a large number of wind vector cells.

We continued our analysis of the O(10 km) wavelength wind-parallel streaks that we discovered in the SAR images of tropical cyclones. We argue that these streaks are induced by very large aspect ratio roll vortices that form due to a nonlinear Floquet instability of the quasi-periodic low aspect ratio roll containing TCBL mean flow.

WORK COMPLETED

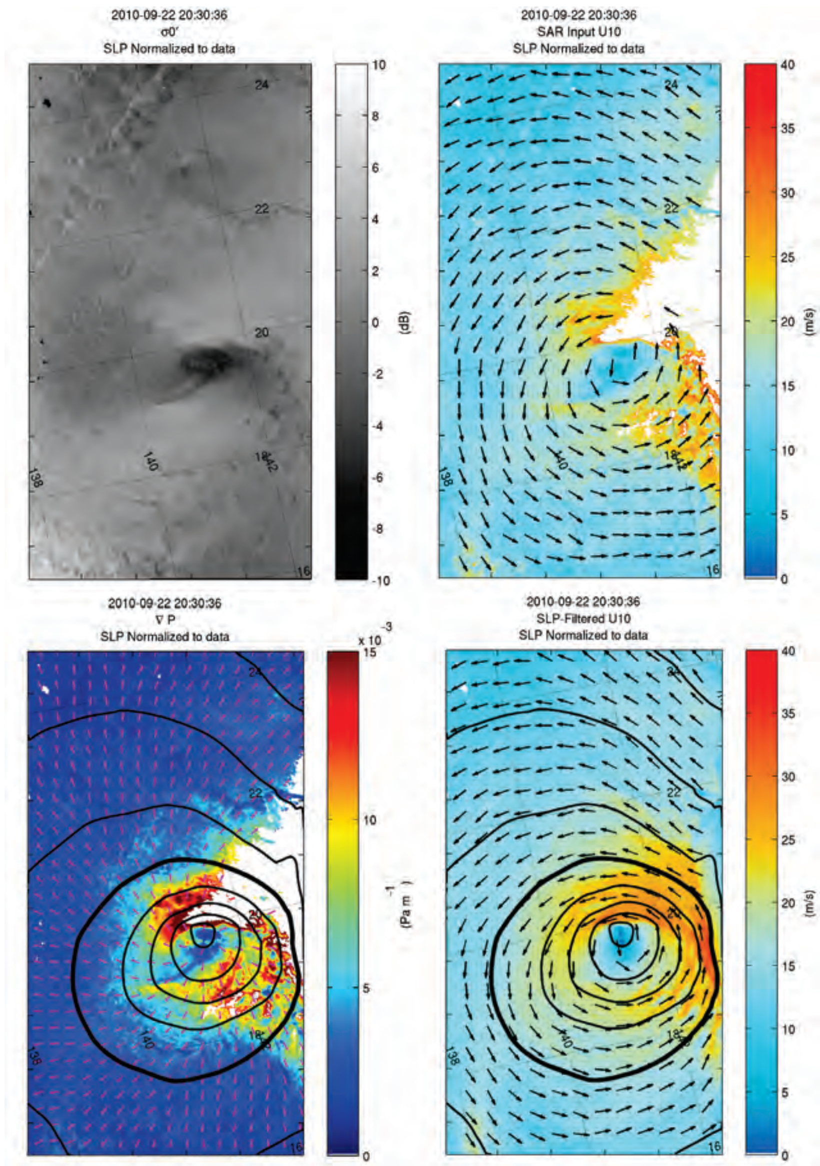

Figure 1: Example of SAR SLP calculation from ITOP typhoon Malakas, 22 September, 2010, 20:30 UTC, (a) Flattened radar backscatter; (b) RAW surface wind processing with mask applied; (c) Surface pressure gradient calculation and fitted sea-level pressure contours; (d) SLP-filtered surface winds.

During year two our main emphasis has been on analyzing and improving our SAR SLP and surface wind vector retrieval methodologies. We continued our examination of the conventional and SAR data, which led to refined results. We published a paper on the O(10 km) wavelength roll vortices and submitted a paper describing the SLP retrievals. We have begun a paper describing the SLP-filtered TC wind vector fields.

RESULTS

An example of the SLP retrieval calculation, from radar backscatter to SLP-filtered winds for typhoon Malakas is shown in Figure 1. Figure 2a shows the comparison of the SAR-retrieved SLP to drop sonde data for five SAR scenes. Overall the agreement is quite good, with an RMSE of 2.5 mb. A better test of the fidelity of the SAR SLP retrievals is to calculate pair-wise SLP differences between drop sondes sampling different regions of the storm. If the overall shape of the SAR-derived SLP is good, then the SAR-derived pairwise pressure differences should match the observed values. If N sondes fall within an image, there we have $N(N-1)/2$ pairs for comparison. Figure 2b shows the results. The

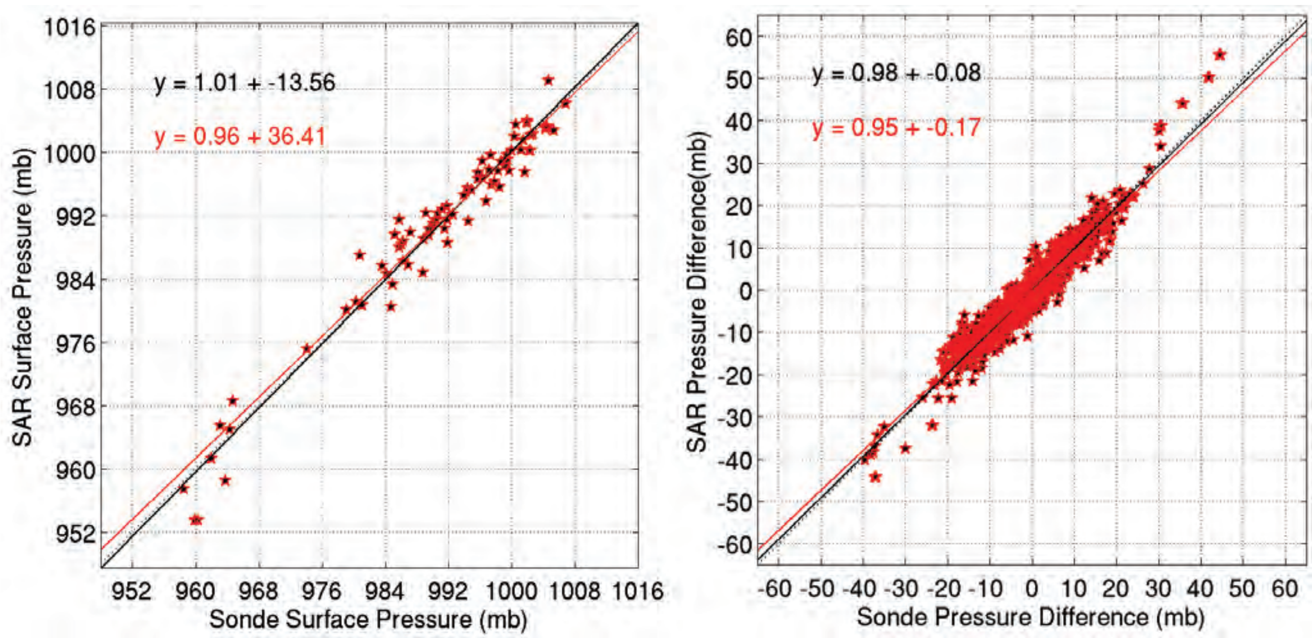

Figure 2: Comparison of SAR-derives surface pressure with drop sonde surface pressure for five SAR scenes. (a) surface pressure. (b) pair-wise surface pressure differences.

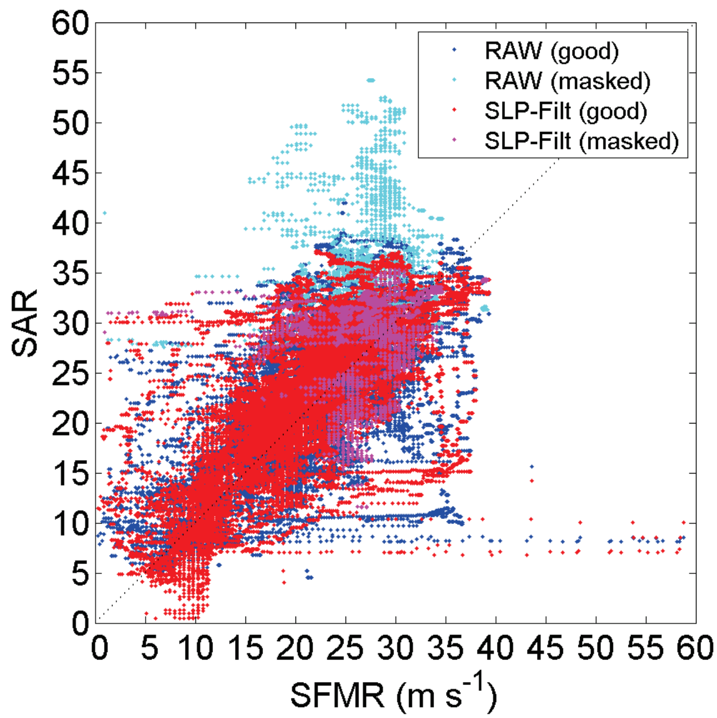

Figure 3: SFMR surface wind speeds compared to SAR surface wind speeds. Blue: high confidence RAW SAR winds; Red: Corresponding SLP-filtered; Cyan: RAW winds in masked regions; Magenta: Corresponding SLP-filtered winds.

RMSE is 3.5 mb. All of the storms considered here were either Category 1 or 2. From these results, we conclude that the overall accuracy of the SAR SLP retrieval for lower intensity storms is around 3.5 mb, which is quite good. In the SAR collection, we have only two images of stronger with in situ data. However, quality issues remain with the surface wind retrievals for these images that result in problems with the pressure gradient and SLP calculations.

Figure 3 shows a comparison of air-borne stepped frequency microwave radiometer (SFMR) surface wind speeds to the SAR surface wind speeds for the same five scenes. The scatter plot shows both the RAW SAR winds from the standard processing and the SLP-filtered winds. Overall, the RAW and SLP-filtered winds are quite consistent with each other and with the SFMR winds. The RMSE for SFMR winds relative to drop sondes is around 5 m s^{-1}. The results for each wind product are divided into the examples from the highest quality RAW winds and those that fell within the masked region (i.e. less certain

SAR wind retrievals). The most notable grouping of data points is the RAW winds that were retrieved in the masked region, which are clearly much too high compared to SFMR. The SLP-filtered winds retrieved in the masked region, however, are consistent with those from the unmasked regions. The RMSE for each wind product relative to SFMR are shown in Table 1. Overall the SLP-filtered surface wind speeds are consistent with SFMR in both the masked and unmasked portion of the SAR image while the RMSE for the RAW winds increases in the masked regions. This shows that the masks are useful at identifying the regions where the RAW processing is less reliable and that it is possible to improve the wind retrievals in these masked regions.

Table 1: RMSE: SFMR to SAR winds

RMSE ($m\ s^{-1}$)	Good Only N = 31,292	Masked Only N = 6,767	All N = 38,059
RAW	5.7	8.6	7.4
SLP-Filtered	5.5	5.4	5.4

IMPACT/APPLICATIONS

The research in this proposal addresses many fundamental issues in TC research. TC intensity is characterized by a combination of maximum surface wind speed and minimum the pressure drop from the last closed pressure contour. The methods developed here are the first steps in routinely evaluating from space these parameters at 1 km spatial resolution and with accuracies approaching those of airborne observations. Potential advantages of SAR over airborne observations are greater coverage, multiple basins and lower cost. Further research is necessary to further evaluate the technique and to extend the methodology for TCs in the higher Saffir-Simpson scales.

PUBLICATIONS

Foster, RC 2013: Signature of large aspect ratio roll vortices in SAR images of tropical cyclones, *Oceanography*, **26**(2):58–67. [in press, refereed, invited].

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